SCOURING PROCESSES IN HARBOUR BASINS DURING THE DOCKING AND UNDOCKING MANOEUVRING: LABORATORY EXPERIMENTS

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Abstract

Scouring processes due to manoeuvring actions can produce big consequences on the stability of harbour structures such as docks and protecting dikes. As a consequence, the sedimentation of the eroded sediment reduces the total depth of the harbour basin and navigation channel. At the same time, contaminants settled at the bed of the harbour basins may be resuspended by the effect of vessel's propellers and produce an important environmental problem to harbour authorities. Present formulas to compute the total scouring depth have revealed to overestimate the maximum scouring depth or be non-realistic in other cases. Experiments performed at the Marine Engineering Laboratory in LaBassA flume (12x4.6x2.5 m^3) with a twin propeller reduced model of 0.25 m diameter are presented herein. Main propeller and bow thruster conditions are evaluated for three different rotating velocities using a sediment diameter of D50 = 250 µm at bollard pull conditions.

Keywords

Scouring processes, environmental protection, structural safety, physical modelling

1. INTRODUCTION

The last release of The World Association for Waterborne Transport Infrastructure in 2015 was a monographic about scour caused by ships and the berthing protections, [1]. However, both the velocity downstream the propellers and the scouring processes due to vessels manoeuvres have been studied so far.

Efflux velocity or downstream velocity, is the first parameter needed to analyze the seabed erosion, since all the theoretical equations developed so far, use this variable as a dependant variable. Ved velocity, has always been expressed as a function of efflux velocity and is used, in turn, to obtain the maximum scouring depth caused by ships propulsion systems. Although efflux velocity for twin propellers has only been described by [2], [3], [1] proposes to use the expressions for a single propeller with a linear or quadratic superposition hypothesis. Therefore, the axial momentum theory can be used, along with [4], [5] or [6] but always bearing in mind the option decided in order to analyse the variability of the final results for expected erosion. [7] analyses the results of the equations proposed by [1], with twin propellers experimental results with good results for the bed velocity predicted by the German method using a quadratic superposition hypothesis.

Other authors outlying local scouring problems can also be used to estimate the maximum erosion in harbours due to propellers. Most of the literature is based in experimental expressions found in laboratories [8]–[12], and can produce non-realistic values when implemented in real harbours [13].

The present paper is aiming to describe the experimental results of scouring processes in a physical laboratory using twin propellers. In order to reproduce more realistic manoeuvres two different configurations were used: scour produced by main propellers and scour produced by bow-thrusters.

2. EXPERIMENTAL SETUP

Physical experiments were performed at a facility located in the Laboratory of Marine Engineering (LIM) from Technical University of Catalonia (UPC-BarcelonaTech). LaBassA, see Figure 1, is a rectangular concrete tank of 12.5x4.6x2.5 m3 with three lateral windows visually access the experiments in time. A sediment layer with a height hs = 0.55 m was located covering most of LaBassa. The grain size distribution of the sediment layer was D50 = 250 µm and D90 = 375 µm. Two helix, with D_p = 0.25 m, were located at the end of LaBassA with a clearance distance from the bottom of h_p = 0.26 m (see Figure 2) and a separation distance between dem of $a_p = 2Dp$;

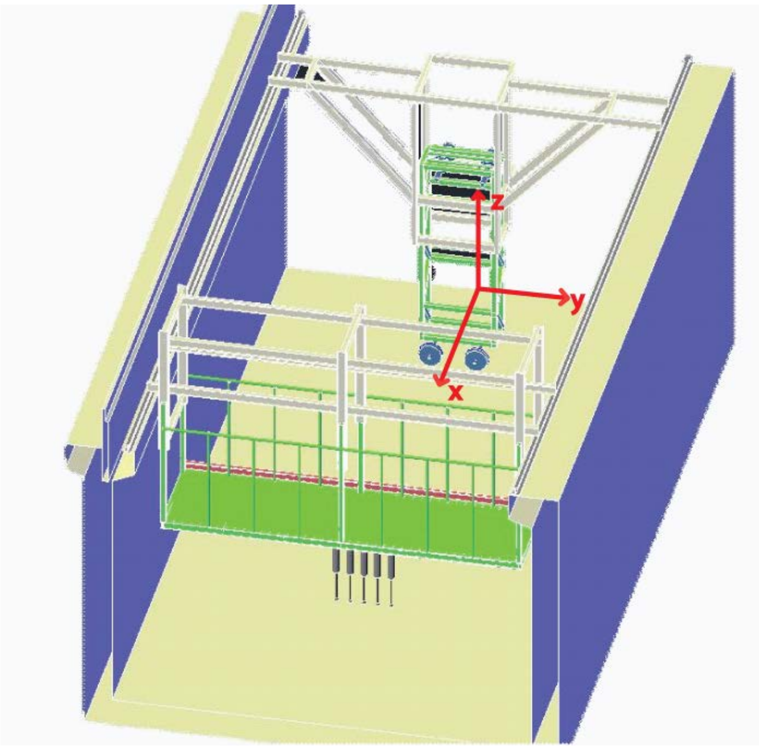

Figure 1. Experimental setup in LaBassA (LIM/UPC-BarcelonaTech). The center of reference is located at the symmetry axis in the bottom of LaBassA.

Experiments were performed to reproduce two configurations in order to obtain comparisons with real situations:

A. Scour produced due to main propellers, which coincides in literature with *unconfined* scenarios.
B. Scour due to bow thrusters close to quay wall, also named *confined* situation.

Twin propellers were located at the lower part of a metallic structure that was hanging from a railroad in each side of LaBassa. The configuration allowed us to move the propellers along the flume and locate them close to the opposite wall in order to reproduce either the main propellers or the bow thruster scouring processes

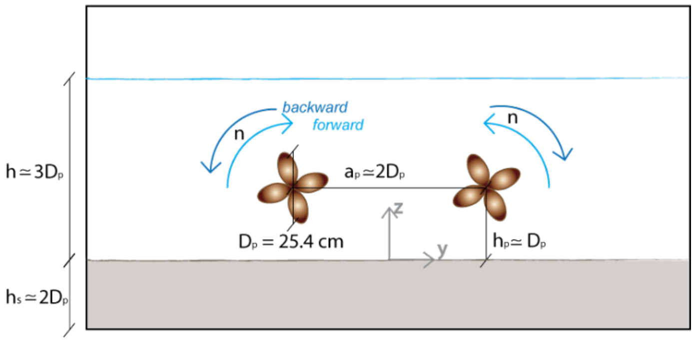

Figure 2. Sketch of the thruster system

A mechanized arm with three degrees of freedom was suspended from a footbridge placed at the same railroads as the propellers metallic structure. Three photoelectric sensors, Efector200-O1D100, were used to locate the position in the x-y-z coordinate system of the mechanized arm. The z-component was placed inside a cylindrical Perspex tank in order to acquire data without flowing out the water in LaBassa. Scouring holes were measured after scanning the sediment bed with 13 longitudinal profiles and 11 transversal profiles, located as detailed in Table 1. The centre of coordinates for each scenario is shown in Figure 3 and located at the propellers plane for the main propeller scenario and the end of the tank for the bow thruster scenario.

Table 1. Position of the scanning profiles. D_p is the propeller diameter

Longitudinal		Transversal			
		Main Propellers		Bow thrusters	
# name	y/a_p	# name	x/D_p	# name	x/D_p
Y-5	-3.0	X0	0.5	X0	1.5
Y-4	-2.5	X1	1.5	X1	2.5
Y-3	-2.0	X2	2.7	X2	3.5
Y-2	-1.5	X3	3.7	X3	4.5
H1	-1.0	X4	4.7	X4	5.5
Y-1	-0.5	X5	5.7	X5	6.5
Y0	0.0	X6	6.6	X6	7.5
Y1	0.5	X7	7.7	X7	8.3
H2	1.0	X8	8.6	X8	9.3
Y2	1.5	X9	9.6	X9	10.3
Y3	2.0	X10	10.6	X10	12.3
Y4	2.5	X11	11.6	X11	14.2
Y5	3.0				

Figure 2 plots the thruster system with the main distances used during the setup of the experiments. The rotating system to simulate the undocking manoeuvring was named forward and was used for the main propellers and bow thrusters configuration. The docking manoeuvring was reproduced after switching the speed direction of both propellers and was only used with the bow thrusters configuration. Errors in the speed rotation were of the order of 10% with a low difference of 3% from one propeller to the other.

Three different rotating velocities were used for the two docking scenarios, n = 300, 350, 400 rpm, and only the maximum rotating speed was used for the docking and undocking case.

2.1 MAIN PROPELLERS

Experiments performed to reproduce the scour caused by the action of twin non-ducted main propellers were done locating the helices at one end of LaBassA in order to avoid the influence of the other end of the tank, as seen in Figure 3. However, the convective cells created in the tank influenced the jet originated by the helices. Thus, one can consider that the influence of the helices opposite end is negligible, but side walls are clearly affecting the scouring results.

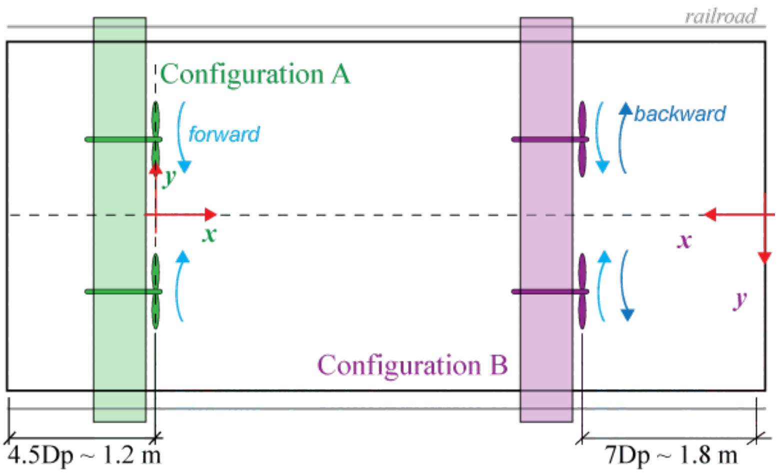

Figure 3. Sketch of the experimental configurations for the two scenarios: A) Main twin-propellers; B) Non-ducted bow thrusters

The scouring action caused by main propellers was simulated by performing sequences of 5 hours run, except the first run of 10 minutes which tried to reproduce the scaled time of a docking and undocking maneuvering, concurrently.

2.2 BOW THRUSTERS

The scour produced by non-ducted bow thrusters was reproduced by moving the metallic structures holding the propellers to a distance of $7D_p$, as shown in Figure 3.

For each experiment, sets of 5 minutes with the forward speed were used to evaluate the evolution of the scouring action of the twin propellers, from 5 to 25 minutes. This sequence was used in order to scale the duration of a docking manoeuvring action of a cruise vessel without tugboat or pilot along an entire week.

In order to reproduce a more realistic manoeuvre, we did a second type of experiments with the bow thruster configuration. Thus, a series of 5 minutes alternating forward (undocking) and backward (docking) speed rotation, starting from an undocking manoeuvre (forward design).

The difference in the time analysis between the main propeller, 5 hours run, and the bow thruster configuration, 5 minutes run, was aiming to, respectively, find the asymptotic state (described by [14] around 48 hours) and reproduce the reality as much as possible.

3. RESULTS

3.1 MAIN PROPELLERS

Results found after analysing the experiments performed with the main propellers configuration revealed that the stationary time was not reached before 20 hours run. However, experiments were stopped after 20 hours because the sediment layer used was already eroded at some points of the sediment layer.

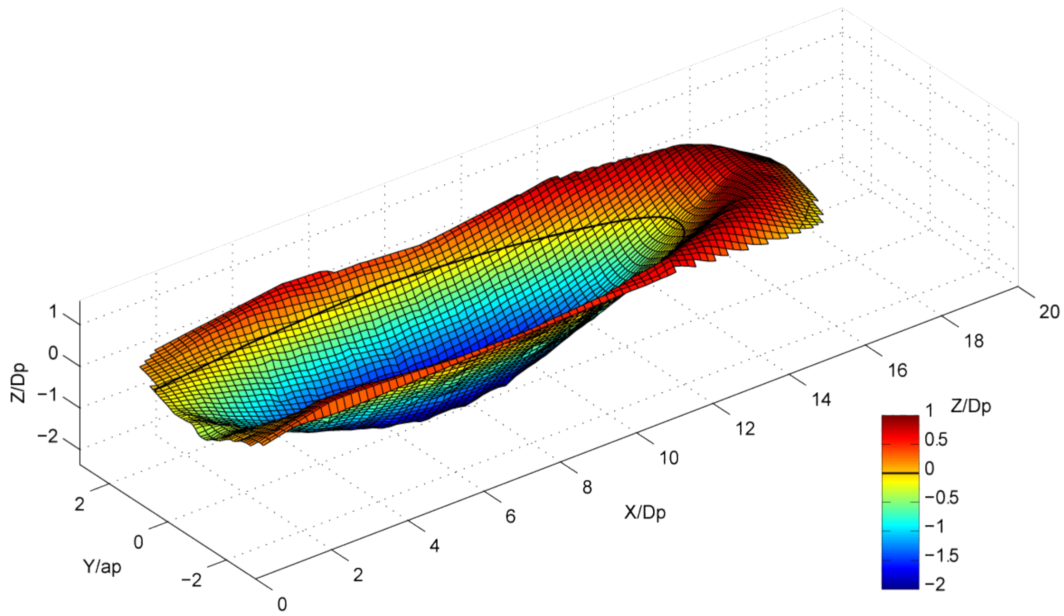

Figure 4. Scour due to main propellers after 15 hours running at 350 rpm.

Figure 4 plots a 3D rendering reproduction of the scouring hole created by the propellers rotating at 350 rpm with a maximum scouring depth of up to $1.8D_p$ and a maximum eroded height of around D_p. In the case of twin propellers, the scouring pattern turns out to be almost symmetric, since the rotating effect observed by [14] for one propeller experiments is compensated with the second propeller. This effect is also confirmed in the other scenarios studied herein.

The scouring evolution of the centerline is shown in Figure 5 for the scenario of 400rpm. As detailed above, the concrete bottom of LaBassA is reached after 20 hours of experiment requiring a thicker layer of sediments from the beginning of the experiments.

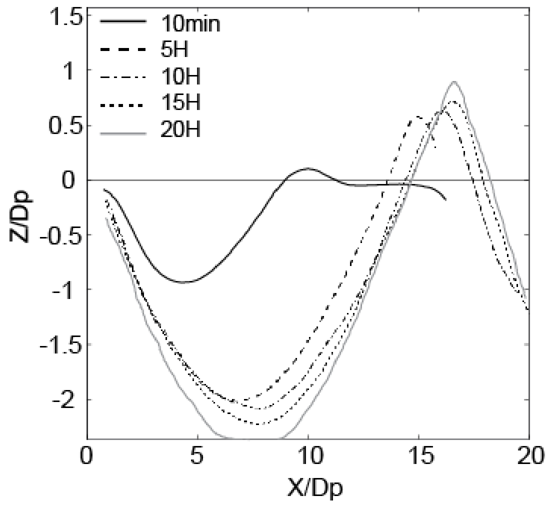

Figure 5. Evolution of the centerline (Y0) of the scouring process for main propellers with a speed revolution of 400 rpm

Figure 5 shows how the distance from the propellers plane and the maximum scouring point increases simultaneously with the deposited height. Thus, the scouring hole increases in length and width, settling the sediment to an external ring that surrounds the main eroded hole. It is important to point out that the maximum deposited height is not located at the centerline of the scouring hole, but in the lateral zones.

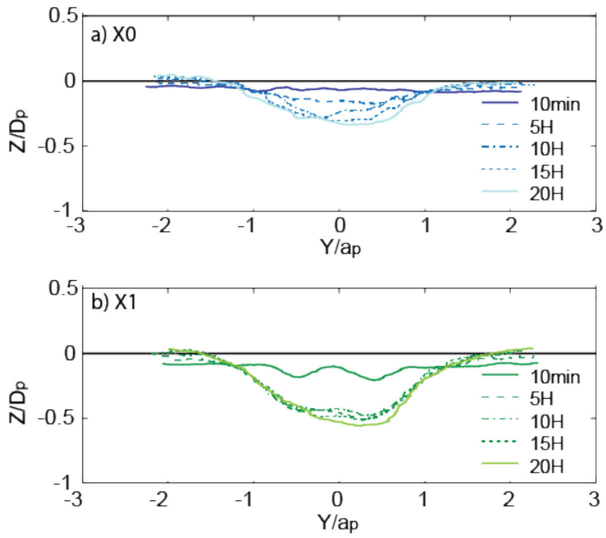

Figure 6. Transversal profiles in the X0 and X1 location, scanned for the 300 rpm scenario.

At the same time, [15]experiments revealed that the influence of twin propellers is very local and disappears in time. Figure 6 illustrates the low effect of separate propellers in our experiments. The effect of twin propellers configuration is not perceived in Figure 4, but a closed zoom to the transversal profiles close to the propellers plane is shown in Figure 6. The twin propeller's influence is only detected in the X1 profile, Figure 6b, particularly at the beginning of the experiment. However, after 15 hours of experiment the twin propeller effects close to the propeller plane disappear completely.

The main problem for harbor authorities may not only be the maximum scouring depth caused by the main propellers, but also the deposition and the further reduction in the basin depth, as detailed by [13]. Figure 7a plots the evolution of the maximum scouring depth, ε_{max}, where the asymptotic state is clearly not reached, as described previously. The behavior of the three scenarios is consistent with qualitative previous experiments (e.g. [1], [14], [16]) and can be fitted within a log-log profile. This work is left for further publications, where more scenarios varying the clearance distance and the propeller pitch will be included.

On the other hand, the maximum deposition height, s_{max}, plotted in Figure 7b shows a clear semi-logarithmic tendency, being proportional to the time logarithm.

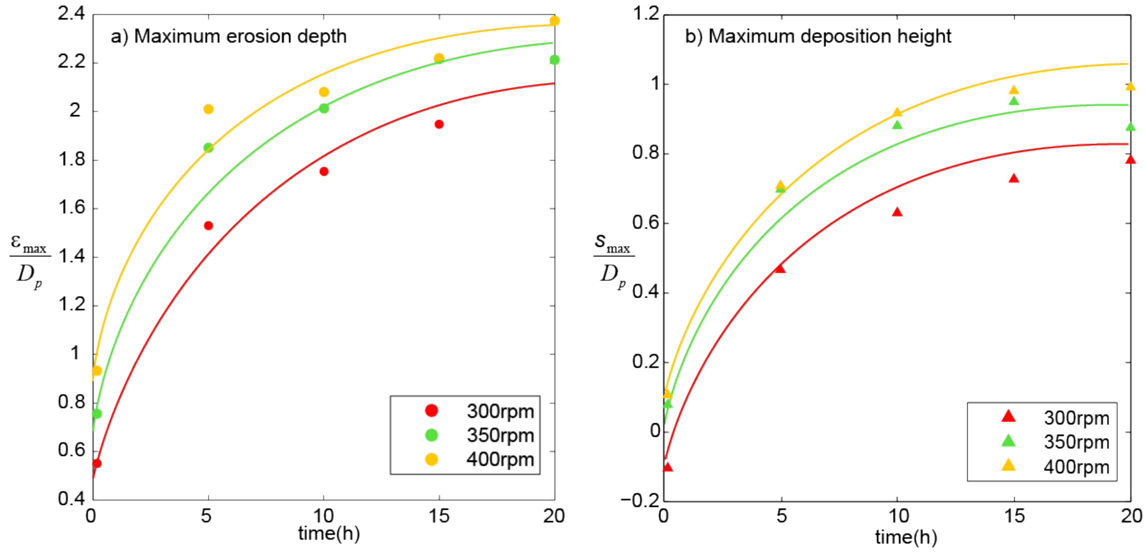

Figure 7. Evolution of the a) maximum scouring depth and b) maximum deposition height

3.2 BOW THRUSTERS

When the propellers are placed close to one end, the model scenario is trying to reproduce bow thruster conditions. In this case, as detailed in the previous section, helices are located $7D_p$ meters from the opposite wall. Besides, experiments in these scenarios were performed using 5 minutes runs instead of 5 hours, trying to simulate the entire process of docking and undocking manoeuvring.

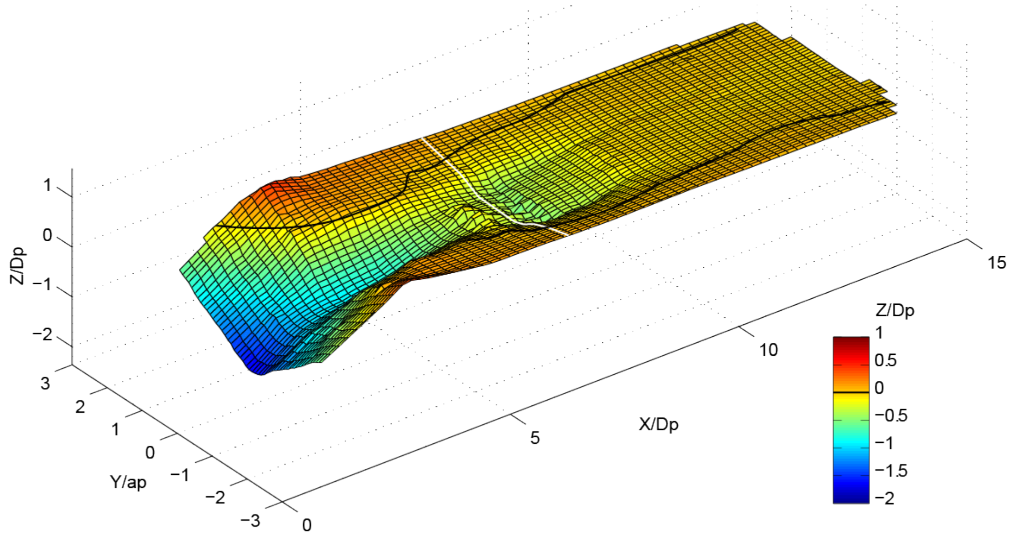

Figure 8. Rendering of the scour action produced by twin bow thrusters moving forward after 15 minutes run at 400 rpm. White line is the location of the helix plane.

Figure 8 shows a 3D render plot of the results, with a clear scouring hole formed close to the wall (x=0). The effects upstream of the propellers shall be neglected since they are clearly influenced by the experimental setup, and the shape of the vessels hull is not included in this research. Underneath the propellers hub, there is a small sedimentation area, mainly due to the negative pressure flow field created at this part of the propellers. This phenomenon may also occur in real vessels, however, the manoeuvring process balances the small sedimentation hill, as reported by [16].

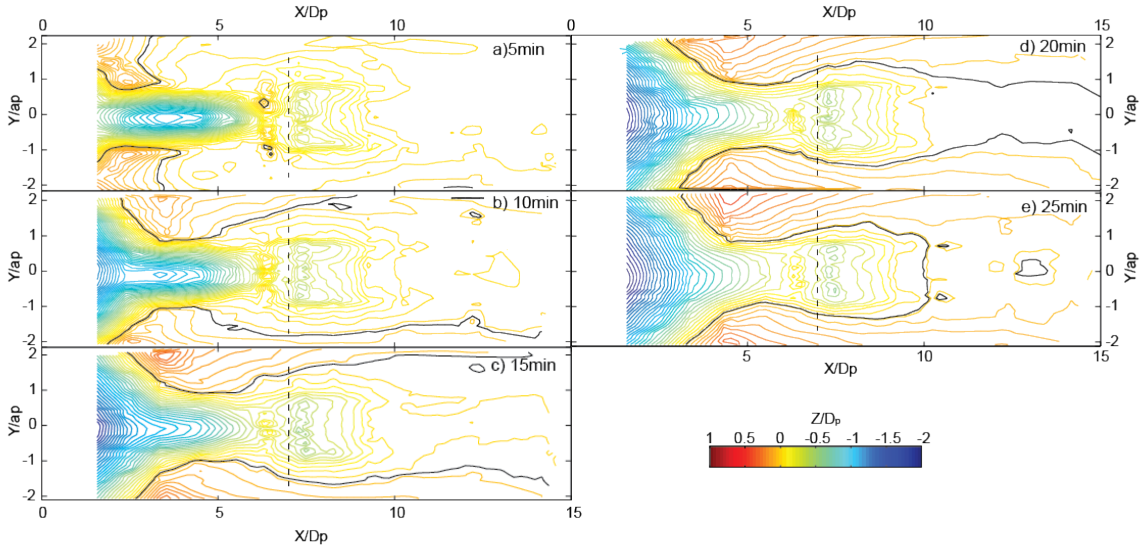

Figure 9. Contour plot evolution of bow-thrusters scenario, with a speed revolution of 400rpm. Dashed line is the position of the helix plane.

Again, the asymptotic state is not reached after 25 minutes run, but this was not the mail goal of the present experiments. In Figure 9, the upstream scouring hole is static throughout the experiments, but the main scouring hole located at the wall keeps growing in time. The blank zone in Figure 9 is due to the set-up of the scanning probe. In fact, the increasing rate of the maximum scouring depth, Figure 10, follows an exponential trend.

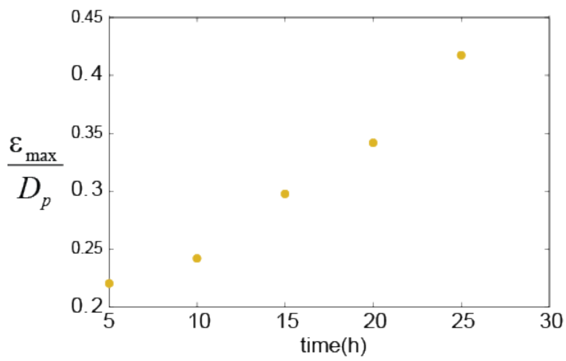

Figure 10. Maximum scouring depth evolution for the bow-thrusters scenario with a speed revolution of 400rpm.

If the former case, using only forward speed conditions is compared to a back and forth speed conditions of the bow thrusters, there is a clear change, particularly upstream of the propellers. In this case, the shape of the facility built to support the helices is a clear influence in the formation of the upstream scouring hole. However, the present experiments shall be used as a guide to understand the process of the scouring hole due to the docking and undocking process.

In Figure 11, a 3D render scan of the scouring hole produced after 15 minutes running with a series of 5 minutes forth and back shows how the magnitude of the hole created close to the wall is of the same order of magnitude of the scouring hole formed upstream of the propellers.

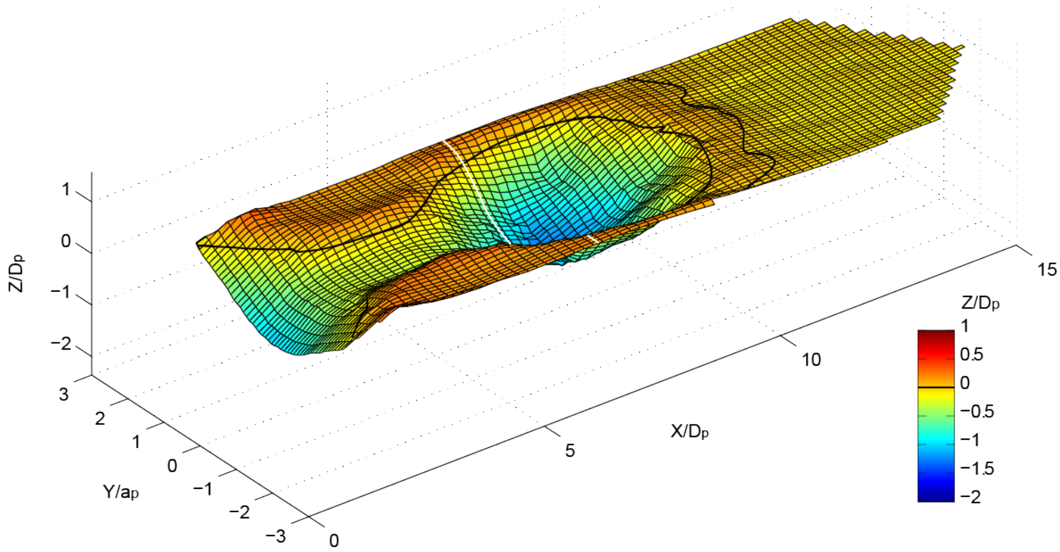

Figure 11. 400rpm 15 min forward

The sequence of speed direction produced an interesting phenomenon which consisted on the scouring process in the downstream hole, while the sediment was settled in the upstream cavity and opposite. Figure 12 shows clearly this process, with the formation of a connecting channel between them. This channel was formed after a forward (docking) run and was destroyed after a backwards run (undocking)

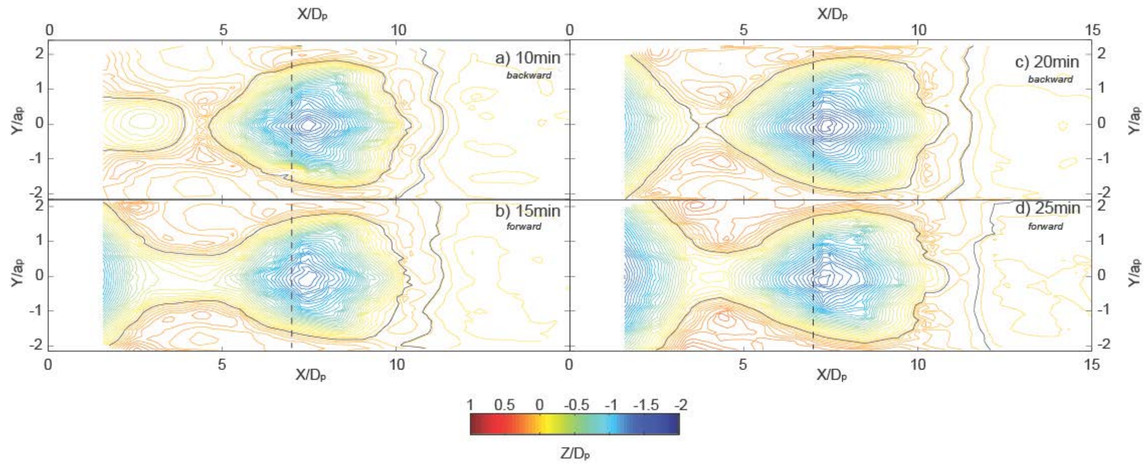

Figure 12. Contour plot evolution of the back and forth scenario with a speed revolution of 400 rpm using the bow-thrusters configuration. Dashed line is the position of the helix plane.

4. DISCUSSION

A first comparison between the two propeller experimental configuration confirms what [17] concluded with their experiments: the effect of the boundary substantially increases the potential erosion caused by propellers. In the paper of [17] experiments were done using a single propeller and the maximum scouring depth was around twice the depth caused by main propellers. At the same time, the deposition of the eroded sediment settled close to the wall in the neighborhood of the scouring hole. In the present research, only the 10 minutes set up can be compared between scenarios, being the maximum scouring depth found for bow-thrusters configuration almost 4 times larger than the same variable for main propellers. Therefore, the number of propellers is clearly a variable to take into account when computing the scouring effects produced by vessels, along with the engine power, the pitch and the clearance distance.

When the two scenarios of the bow thruster configuration are compared, it is clear that the back and forth scenario is less dangerous for quay structures since one maneuver scouring process balances the opposite maneuver. However, it seems that in the asymptotic state both scenarios will yield the same maximum scouring depth close to the wall, being the more realistic scenario the worst case. Besides, the docking and undocking maneuvering produces two different cavities with twice the eroded volume as the docking maneuvering with the subsequent deposition problems along the harbor basin.

The experiments presented herein reveal what has already been described in real harbors: the high scouring capacity of the bow thrusters and main propellers close to the wall, producing big problems on the stability of quay structures. The consequent problem of the sedimentation is also very important since the reduction of the depth in some areas of the harbor basins may force the vessels to maneuver in order to avoid these zones and finally declare the harbor basin inoperative for certain vessels with the consequent economic losses.

The main propellers results are more likely to occur in navigation channels than in harbor basins. Therefore, results found during this investigations shall be considered as absolute values for harbor authorities and protection designs. However, if this is the situation, the main problem for harbor structures and operational system will not be the scouring process but the zone where the eroded sediment is deposited. This is clearly influenced by the maneuvering actions of the vessels in the navigation channel or basin. Besides, the deposition of contaminants at the bed of the harbor has to be tracked by studying the effects of main propellers when the vessel transits the contaminated zone.

The expressions detailed in [14], [17] and [1] were applied to the data of the experiments with results far from the experimental data. It is left for further studies a detailed description of the data and the problems in the formulations. Moreover, a new expression to estimate maximum scouring and maximum sedimentation height is now under development and will be published.

5. CONCLUSIONS

Results obtained after modelling main propulsion system and bow-thrusters using a laboratory experimental facility built with a twin propeller design are found to be different from the previous data using a single propeller (i.e. [17], [11]).

First, main propeller experiments can be used as a guideline to obtain the erosion caused by vessels when manoeuvring in navigation channels or areas with no rear influence of a wall. This is important in order to estimate the amount of bedload accumulated close to the walls of the navigation channel which will reduce the depth of the area and can also cause environmental problems to harbour authorities.

Second, in terms of the bow thrusters influence on the stability of quay structures, it is clear that the effect caused by the propellers is very important and can cause severe damages to the structures, particularly at the beginning of the undocking manoeuvers and at the end of the docking manoeuvers. Therefore, the prediction of the total erosion is important to design the protections or implement some manoeuvring operations in order to minimize such effect. The maximum erosion caused during docking and undocking manoeuvers is more than twice the erosion occasioned by the main propellers in an open channel. However, the influence of main propellers during the docking and undocking manoeuvring must be taken into account as well. In this regarding, the estimation of erosion caused by main propellers close to quay walls can be computed with the formulations proposed by bow-thrusters close to the wall or confined areas, as seen in literature.

Finally, the sedimentation caused by the eroded sediment is more important when the main propellers in a navigation channel were analysed. However, the settling of the sediment scoured by bow-thrusters may be more uniform and influenced by the manoeuvring actions in the harbour basin. To prevent the accumulation of sediments in certain zones, a detailed study of the manoeuvers needs to be done, and further small changes in the manoeuvres may prevent the harbour basin to be inoperative in the same zones.

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